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An evaluation of magnetic mounting of accelerometers

Colley, Donald Vernon

Monterey, California. Naval Postgraduate School

AN EVALUATION OF MAGNETIC MOUNTING
OF ACCELEROMETERS

Donald Vernon Colley

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

An Evaluation of Magnetic Mounting

of Accelerometers

by

Donald Vernon Colley

December 1974

Thesis Advisor: R. E. Newton

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An Evaluation of Magnetic Mounting

of Accelerometers

by

Donald Vernon Colley
Lieutenant, United States Navy
B.S., United States Naval Academy, 1966

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requirements for the degree of

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The performance of magnetic clamps as a means of attaching accelerometers for machinery vibration surveys is investigated. Three conditions that might adversely affect magnetic clamp effectiveness are looked at in detail: (1) the presence of cross-motion, (2) the mounting conditions, and (3) the presence of high levels of acceleration. Results are given for six commercially produced magnetic clamps. Cross-motion and high acceleration are found to have little effect on magnetic clamp response to the extent tested. Improper mounting is found to affect response greatly. Procedures are recommended for attachment of clamps and results of tests using these procedures are shown to be reproducible.

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Finally, I am thankful for the many prayers of friends and family, and to God for answering them.

I. INTRODUCTION

The purpose of this work is to investigate the performance of magnetic clamps as a means of mounting accelerometers for vibration measurements. Previous work has shown that at higher frequencies readings obtained with accelerometers mounted magnetically deviate considerably from true values.

In this investigation tests were conducted to gain further insight into the behavior of the magnetic clamp. Specifically it was undertaken to determine what effect, if any, is caused by (1) cross-motion, (2) mounting surface conditions, (3) high levels of acceleration.

The Naval Ship Engineering Center, Philadelphia Division, (NAVSECPHILADIV), provided five commercially available magnetic clamps for testing. Spectral Dynamics Corporation of San Diego provided an additional magnet, along with a Dymac model M90 accelerometer and kit.

II. MOTIVATION

The motivation for this work lies in the widespread interest in machinery vibration monitoring. Maintenance engineers in many fields are utilizing vibration data as a diagnostic tool, thus eliminating many costly open-and-inspect maintenance checks.

Monitoring systems vary in complexity. At one end of the scale, broad band rms readings are measured at only a few locations. Vibration levels are recorded and compared with specified limits and previous readings. Trends are noted as indications of impending trouble.

At the other end of the scale there are systems which continuously monitor vibration at many locations. Spectrum analysis of the signals is available whenever desired and data is stored for future reference.

Continuous vibration monitoring can provide information for maintenance purposes and control purposes at the same time. When the vibration of a machine reaches a certain level, an automatic shut-down device may be triggered to take the machine off the line and start up a standby.

Spectrum analysis of a machinery vibration signal allows one to determine the frequencies at which energy is concentrated. If there is an increase in vibration level, the frequency at which the increase appears in the spectrum, or signature, of the signal often gives an indication of the cause of the increased vibration level. References 1 through 3 describe vibration spectrum monitoring in more detail.

Applications are being made in the fields of gas turbines, turbo-generators, process plants, and marine engineering. References 4 through 7 give information relating to specific applications.

Reference 8 describes NAVSECPHILADIV's program of shipboard vibration data collection and analysis. The purpose of this program has been to provide additional information upon which to base decisions regarding shipyard work packages.

References 9 and 10 give the history and status of efforts to bring vibration monitoring within the capability of shipboard personnel. The cornerstone of any such system is the validity of the data collected. In the actual procedure of data collection there are many things that can happen to invalidate the data obtained. The composition of a monitoring team sent aboard ship by NAVSECPHILADIV gives some indication of the complexity of present procedure and equipment. The make-up of a team to survey an aircraft carrier is typically one mechanical engineer, three electronic engineers, two electronic technicians, one instrumentation engineer, and one instrument mechanic.

To make vibration monitoring a routine ship's force function will require simpler equipment and procedures. Any improvements must still minimize the probability of obtaining spurious data.

One simplification, the subject of this paper, is the possible use of magnetic clamps to attach accelerometers to the machine to be monitored. Present procedure calls for a steel block to be welded in place at the point of measurement. Accelerometers are then attached by studs screwed

into this block. The chief advantage of this method is that it yields highly reliable data. Disadvantages lie in the difficulty encountered in welding the block to the machine, maintaining the block surface free of rust and scratches, and attaching accelerometers in hard-to-reach locations.

Magnetic clamps offer one chief advantage: ease of attachment. Although a flat, smooth surface must be provided for attachment, this would not be as difficult to provide and maintain as the block presently used.

The main disadvantage of using magnetic clamps, as mentioned before, is their lack of accuracy at higher frequencies.

III. PREVIOUS WORK

Previous work has been done to determine the frequency response of the magnet-accelerometer combination.

Whalen and Hargest [Ref. 11] reported flat response (± 2 dB) between 20 and 2000 Hz for the General Radio P35 magnet and Endevco 2217 accelerometer. They observed a resonance of 23 dB at slightly less than 5000 Hz.

Fedena [Ref. 12] reported 2 dB deviation in response at 4800 Hz using the General Radio P35 magnet and Endevco 2234 accelerometer. This was the best response obtained during a number of tests. Silicone grease was used between the magnet and the surface to which it was attached. The response was somewhat worse with a dry mounted magnet.

Miller [Ref. 13] reported the results of using a magnet and a steel mounting adaptor. The magnet appeared similar to the P35, but was not identified. The mounting adaptor is a flat steel disk epoxied to the surface of the vibration source. The magnet was then attached to the disk. With this combination he observed a resonance at about 16 kHz. He recommends, with ideal mounting conditions, an upper limit of 8000 Hz when accuracy within 2 dB is desired.

As can be seen from this resumé of previous results, there is significant variation in the upper frequency limit of acceptable response.

Since practically all the frequencies of interest are below 2000 Hz (120,000 cpm), it might be argued that one is safe in using the magnetic

clamp. However, an important question should be answered before accepting this line of reasoning. Do the conditions under which machinery vibration data must be taken cause the response to be significantly different than that predicted from laboratory tests?

Actual conditions vary from laboratory conditions in at least three ways. The actual motion to be measured is not sinusoidal. It consists primarily of periodic motion with components at many frequencies present at all times. The laboratory tests were made with a swept sinusoid. Thus the motion consisted of only one frequency at a given time. Actual motion is multi-directional as opposed to unidirectional as in the laboratory tests. Finally, actual conditions increase the probability that the surface to which the magnet would be attached would not be as clean as it would be under laboratory conditions.

A word should be said here about other mounting methods. Epoxy glue and pressure sensitive two-faced tape have been tested. Epoxy appears the most promising. It was used in the course of this investigation as a means of attaching mounting studs to two of the magnetic clamps. On three occasions these bonds broke and had to be re-glued.

IV. THE EFFECT OF CROSS-MOTION

Motion measurements in the shipboard environment usually involve significant motion along at least two orthogonal axes at the accelerometer mounting location. Since previous tests were restricted to uniaxial inputs, it was decided at the outset to include in this investigation a study of the effects of cross-motion on the fidelity of magnetically mounted accelerometers. The magnets tested required minimal force to start them sliding parallel to the surface to which they were attached. This force was measured with a hand-held spring scale and found to be from 12% to 22% of the normal force required to pull the magnet from the surface.

These forces, along with the mass of each magnet-accelerometer combination, were used to calculate the acceleration at which the inertia force should overcome the magnetic attractive force. Table I lists these acceleration levels along with further mounting data for each magnet-accelerometer combination.

To determine what effect cross-motion might have on frequency response required the design of a special test fixture. The purpose of the design was to provide a test surface for the attachment of magnets which would allow motion in two orthogonal directions. A sketch of the test fixture is shown in Figure 1.

To accomplish this two shakers were arranged at right angles. A single 4"x4"x 1"steel test block was attached to both shakers by means

Table I. Mounting data and calculated pull-off and slide accelerations for each magnetic clamp used. GR = GENERAL RADIO, EN = ENDEVCO, SD = SPECTRAL DYNAMICS

MAGNETIC CLAMP	ACCELEROMETER	METHOD USED TO ATTACH ACCELEROMETER TO MAGNET	ACCELERATION AT WHICH INTERIA FORCE EQUALS STATIC PERPENDICULAR PULL-OFF FORCE (g,rms) $\pm$ 2g	ACCELERATION AT WHICH INERTIA FORCE EQUALS STATIC FORCE TO START CLAMP SLIDING (g,rms) $\pm$ 1g
GR 1560 P35	EN2233M7	EN 2986B insulated stud with nut	60	8.5
GR 1560 4020 (#1)	EN2233M7	EN 2988 cementable stud with epoxy	23	4.0
GR 1560 4020 (#2)	EN2233M7	EN 2980B insulated stud with nut	19	3.0
SD 4400	EN2233M7	solid stud	27	5.2
SD 4400	SD DYMACM90	solid stud	17	3.3

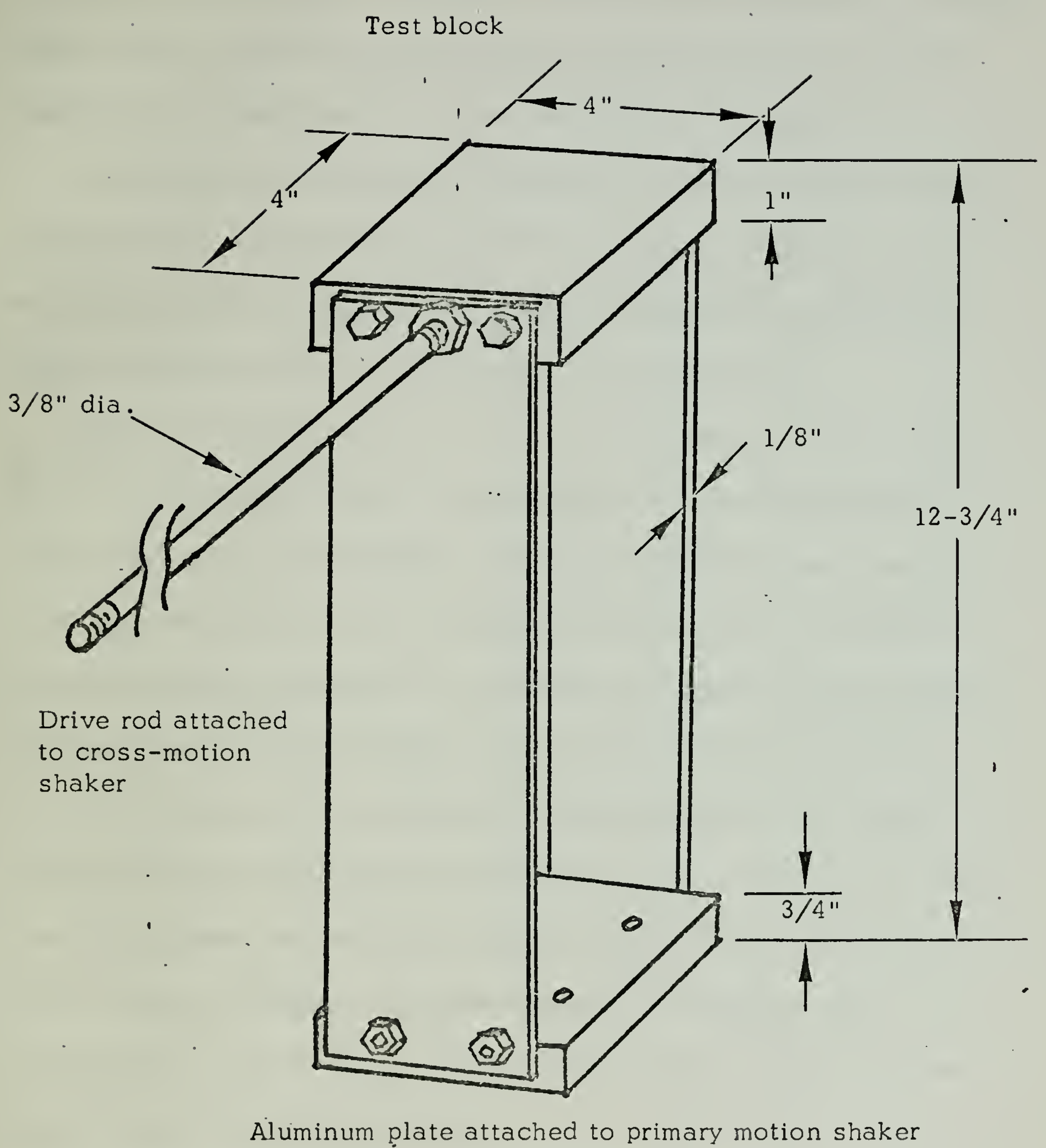


Figure 1. Sketch of cross-motion test fixture. Steel was used for all parts except for the aluminum base plate. Not in view is the 1"x1"x1-1/4" reference block welded to the center of the bottom face of the test block.

of slender members. The axial stiffness of the members was much greater than their lateral stiffness. Thus the test block was constrained to follow shaker motion oriented along the member's axis while at the same time offer only slight resistance to forces perpendicular to the members.

The members' low natural frequencies of lateral vibration prevented transmission of excessive moments from one shaker to the other at the frequencies used in the tests. The shaker manufacturer's instruction manual cautioned against such moments and lateral forces.

The top surface of the test block was machined to a surface roughness of 25 microinches (rms). This surface served as the attachment location for the magnetic clamps. Numerous attachments and removals of the magnets produced some scratching of the surface. The depth of the scratches was not measured, but surface roughness in the disturbed area increased 10 to 15 microinches (rms) in the course of the tests.

A 1"x1"x1-1/4" steel reference block was welded to the bottom of the test plate. Each exposed face of this block was drilled and tapped to receive an accelerometer mounting stud. Machining of each face produced a surface roughness of approximately 35 microinches (rms). An accelerometer to measure cross-motion and the reference accelerometer were attached to the reference block.

A Calidyne model 219 electromagnetic shaker provided motion in the primary, or vertical, direction. A Ling S-11 control system controlled frequency and acceleration level.

A Calidyne model A88 electromagnetic shaker provided horizontal, or cross-motion. Control equipment consisted of a Calidyne model 68 power supply and amplifier, model 102 dc field supply, and a Dymec model DY2200A sweep oscillator.

The shaker arrangement and schematic of the data collection and plotting system are shown in Figure 2.

Accelerometer outputs were amplified and displayed on an oscilloscope. Root mean square (heating value) voltmeters provided accurate measurement of each signal.

For plotting purposes, each voltmeter provided a dc signal proportional to the rms value of the input signal. An Analog Devices model 426 divider was then used to obtain the ratio of the two signals. A dc signal proportional to frequency was obtained from a frequency meter connected so as to measure frequency of motion in the primary (vertical) direction. The dc signals were used to obtain ratio vs. frequency curves on an X-Y plotter. A counter was used for frequency calibration.

Initially, point-by-point data was taken and plotted by hand. The presence of many peaks and valleys, however, rendered this method difficult. Subsequently the X-Y plotter became the primary means of recording data. Data for the M90 accelerometer was taken and plotted by hand. This was necessary to avoid repeated charge amplifier recalibration to make the reference signal comparable with the output of the M603 power unit.

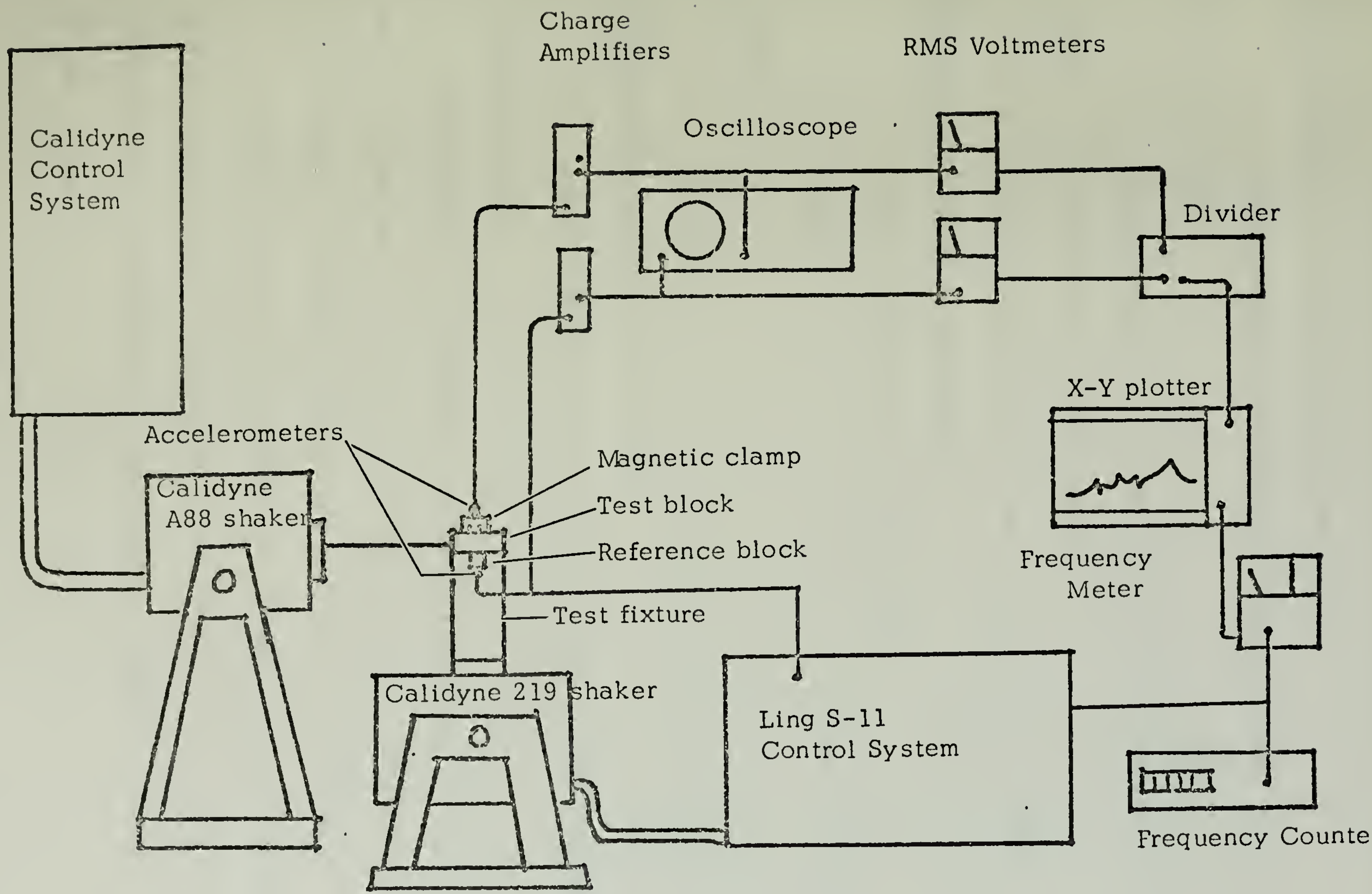


Figure 2. Schematic of shaker, test fixture, and data collection arrangement.

The procedure for each run was as follows:

1. Check all connections and bolts for tightness. No loosening of the test rig was noted throughout the testing.

2. Attach stud mounted reference accelerometers. Allow leads to hang naturally.

3. Wipe clean the legs of the magnetic clamp and the test surface. Inspect to insure cleanliness.

4. Apply film of petroleum base electric motor oil, SAE 20, to each magnet leg and to the surface.

5. Attach magnetic clamp to test surface.

6. Establish acceleration amplitude and frequency of cross-motion.

7. Establish acceleration amplitude of primary motion. Set automatic acceleration level control.

8. Sweep through frequency range with set level of acceleration in primary direction, obtaining ratio vs. frequency data.

For comparison of response without cross-motion to that with cross-motion, the magnet was not disturbed between runs. Between sets of runs, however, the magnet was usually removed and re-attached.

A number of runs using silicone grease instead of oil revealed no apparent difference in performance. Data from runs made with the magnet dry mounted is presented in the next section. Table 2 indicates the range of tests conducted.

Table II. The scope of cross-motion tests conducted. Acceleration is in g,rms. GR = General Radio, SD = Spectral Dynamics. X = test conducted, # = data presented in following figures

MAGNETIC CLAMP	WITHOUT CROSS-MOTION		WITH CROSS-MOTION AT 500 Hz		1 kHz	2kHz	3.8kHz
	2g	4g	2g	4g	4g	4g	4g
GR P35	X	X#	X	X	X	X#	X
GR4020(#1)	X	X#	X	X	X	X#	X
GR4020(#2)	X	X#	X	X	X	X#	X
SD4400	X	X#	X	X#			
SD4400 w/M90	X	X#	X	X#			

Figures 3 through 7 present data from one run of each magnet-accelerometer combination, with and without cross-motion. Figure 3 and all subsequent figures are shown in pages 31 through 41. The ordinate in each graph is the ratio of the acceleration as measured by the magnetically attached accelerometer to that measured by the stud mounted reference accelerometer. The abscissa is the frequency of the shaker motion in the primary (vertical) direction.

Examination of this data reveals that in no case was there significant effect due to the presence of cross-motion. The additional data obtained, as indicated in Table II, likewise revealed no significant degradation of response due to cross-motion. No lowering of resonant frequencies was observed. In a few cases variation in the value of the ratio was noted. There were as many instances in which the ratio decreased with cross-motion as there were in which it increased. Generally the ratio remained nearly the same so there appears to be no correlation with cross-motion at the acceleration levels used in these tests. The capacity of the shaker and the characteristics of the test fixture limited testing to 4g (rms) cross-motion.

Comparison of the response of the various magnets reveals that some peaks occur at the same frequencies whether or not cross-motion is present and regardless of the magnetic clamp being tested. For example, compare the curves in Figures 3, 4, and 5, at approximately 2700 Hz. The possibility of a second harmonic being present in the shaker driving current offers an explanation for this phenomenon. The test fixture

exhibited a resonance at approximately 5400 Hz for motion in the vertical direction. At an exciting frequency of 2700 Hz a second harmonic would coincide with this resonance causing significant motion of the test block at a frequency of 5400 Hz. The higher relative response of the magnet at this frequency would cause the output of the magnet mounted accelerometer to become much higher than that of the stud mounted accelerometer. This would create a peak of the ratio vs. frequency curve at the primary driving frequency of 2700 kHz. Multiple resonances of the test set up make similar analysis for each peak extremely difficult. The use of a tracking filter in the output circuit of each accelerometer is recommended for future tests of this nature. The use of this procedure is reported by Fedena in Reference 12.

V. THE EFFECT OF MAGNET MOUNTING CONDITIONS

The object of this phase of the investigation was to show the effect of various mounting conditions on the magnet-mounted accelerometer. The three conditions considered were: (1) magnet attached using oil in accordance with the procedures given in the previous section; (2) magnet mounted dry (i.e., no oil); (3) magnet mounted as in (1), but with a .001 in. iron wire inserted under one leg of the magnet.

The Calidyne model 219 shaker provided the motion. A steel test plate bolted to the table of the shaker provided a test surface. The surface was ground to an initial surface roughness of 10 microinches (rms). Again, scratches in the surface occurred during the sequence of tests and roughness in the scratched areas increased to approximately 30 microinches (rms).

Two accelerometers mounted side-by-side on the test plate measured the vibration. One accelerometer was stud mounted and the other magnetically mounted. The shaker was oriented so that motion was in the horizontal direction. The data collection and recording system utilized was the same as that used in the cross-motion tests.

Two additional magnets were received from NAVSECPHILADIV prior to the completion of these tests. They were the General Radio 9026 and the B & K Instruments UA0070.

To determine the reliability of results using the standard procedures at least five response curves were obtained for each magnet. The magnets

were removed and reattached to the surface between runs. Figures 8 through 10 show the results of these tests. The best response and the worst response are shown for each magnet.

Comparison of the responses shown in Figure 11 reveals a definite improvement in frequency response with the use of an oil film between magnet and mounting surface. This was true of both the magnets tested.

Figure 12 shows the effect of placing a .001 in. iron wire beneath one leg of the magnetic clamp. A marked effect is observed in both cases, but the nature of that effect appears to be different in each case.

VI. THE EFFECT OF HIGH LEVELS OF ACCELERATION

The purpose of this portion of the work was to subject one of the magnets to an acceleration level at which the magnetic attraction force should be overcome by inertia forces. The static attraction forces were measured with a hand held spring scale. There was considerable variation in the force required to detach a magnet from one attempt to another.

The GR 4020 (#1) magnetic clamp was used for this test. As seen in Table I the magnet should separate from the test surface at an acceleration between 22 and 25g (rms) when oil is used. With the magnet mounted dry the static pulloff forces were between 15 and 22g (rms).

The Calidyne 219 shaker was used for this test. A steel mounting block was bolted to the shaker table. The shaker was tilted so that motion was in the horizontal direction. The data collection system was the same as that used in cross-motion tests, except that data was taken point by point. The procedure for attaching the magnets was as described for the cross-motion tests.

In each test two accelerometers were mounted side-by-side, one mounted with a solid stud and the other with a magnetic clamp. The desired frequency was set and remained constant throughout the test. Acceleration was increased in steps using the stud mounted accelerometer as reference. Readings from each accelerometer were recorded. The readings were converted to g's and the one measurement was plotted

versus the other. Results are shown in Figure 13. The capacity of the shaker limited the tests to a maximum acceleration of 48g.

With the magnetic clamp mounted dry the output wave form of the attached accelerometer became slightly altered at approximately 13g as indicated by the reference accelerometer. At this point the magnetically mounted accelerometer was indicating 22g, an acceleration corresponding to the maximum static pull off force measured for this mounting condition.

At 36g the response of the magnet mounted accelerometer began to increase rapidly. Until this point wave form had only been slightly distorted. At 39g the magnet began to "walk" along the test surface until it reached the edge of the test plate or ran into a bolt.

In the case of the oil mounted magnet no wave form distortion or sliding was noted up to the maximum acceleration of 48g.

VII. CONCLUSIONS

1. Cross-motion of up to 4g (rms) acceleration had no significant effect on the behavior of those magnetic clamps tested.

2. Mounting surface conditions have a significant effect on the response of a magnetically mounted accelerometer.

3. The response of a dry mounted magnet is much worse than that of a magnet mounted using SAE 20 electric motor oil or silicone grease.

4. Inclusion of foreign matter between the magnet and the surface of attachment lowers the maximum useful frequency of a magnet mounted accelerometer.

5. Readings obtained from magnetically mounted accelerometers are valid beyond the threshold acceleration level at which one would expect error, based on static pull off forces.

6. The presence of an oil film is beneficial to magnet performance at high accelerations.

7. Careful adherence to the mounting procedures described in steps 3, 4, and 5 on page 19 will yield reproducible results.

VIII. RECOMMENDATIONS

1. The investigation should be continued to determine whether high frequency components of machinery motion would have an adverse effect on the ability of a magnetic clamp to reproduce the lower frequency spectrum.

2. The use of an oil or silicone grease film for mounting magnetic accelerometer clamps is recommended.

3. When mounting magnet clamps, great care should be taken to exclude foreign matter between magnet and surface.

4. When possible, multiple readings should be obtained at each point of attachment, carefully remounting the magnetic clamp for each run.

APPENDIX A

LIST OF EQUIPMENT

1. Shakers and associated control equipment:

   a. Calidyne model 219 shaker, ser. 23

      Ling S-11 servo control system consisting of:

         S-10 servo control amplifier

         S-12 D&G amplifier

         Dymec model CO-10 cycling oscillator

         CP - 3/4-D amplifier

   b. Calidyne model A88 shaker, ser. 123

      Dymec DY-2200A sweep oscillator

      Calidyne model 68 power supply

      Calidyne model 68 amplifier

      Calidyne model 102 dc field supply

2. Transducers:

   a. Endevco model 2233M7 piezoelectric accelerometers, ser. HA05 and EA16

   b. Spectral Dynamics Dymac M90 general purpose industrial accelerometer, ser. 0008 (with model 604 accelerometer kit)

3. Magnetic clamps and insulated studs:

   a. General Radio model 1560-P35 with Endevco model 2986B insulated stud

b. Two General Radio model 1560-4020. They were arbitrarily given designations of #1 and #2. An Endevco model 2988 cementable stud was epoxied to magnet #1. An Endevco model 2980B insulated stud was attached to #2

c. Spectral Dynamics model 4400. A solid stud was used to mount Endevco 2233 or Dymac M90 to this magnetic clamp.

d. General Radio model 1560-9026, with integral stud

e. B&K model UA0070, with integral stud

4. Data collection and display equipment:

a. Kistler model 503 charge amplifier, ser. 177

b. Endevco model 4477.2 charge amplifier, ser. AF17

c. Hewlett-Packard model 130C oscilloscope, ser. 344-02271

d. Two Hewlett-Packard model 3400A RMS (heating value) voltmeters, ser. 952-12102 and 952-11984

e. Anadex counter, USN, ser. 013592

f. Analog Devices model 426A divider

g. Moseley model 135 X-Y plotter, ser. 706-03366

h. Hewlett-Packard model 5210A frequency meter, ser. 712-00474

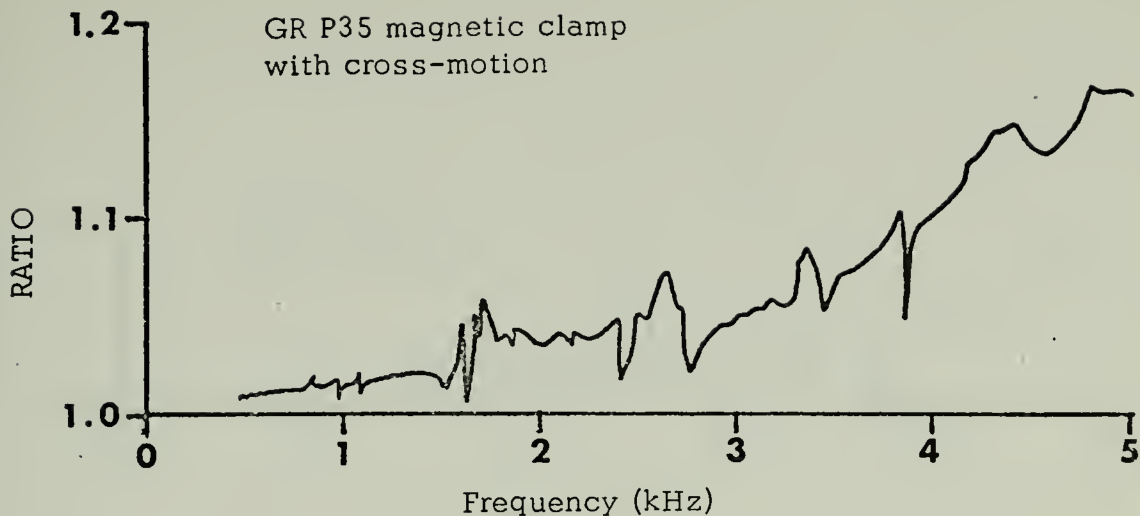
i. Simpson model 2700 dc voltmeter, ser. 1756

5. Surface roughness sensor:

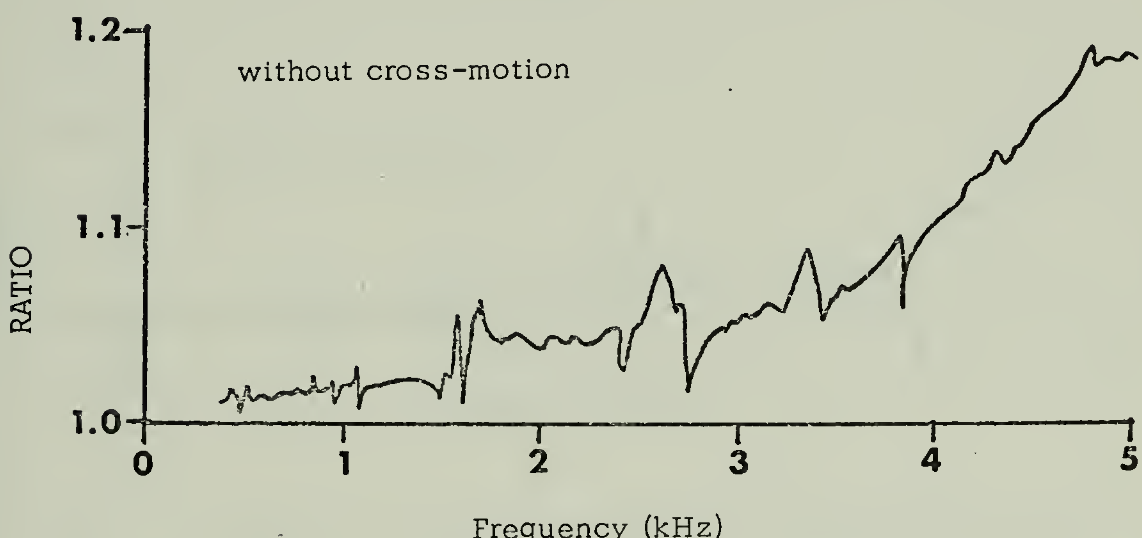
Gould-Clevite model 7100 Surfanalyzer system

6. Spring scale:

Central Scientific Co. 0-30 lb. spring scale



(a)



(b)

Figure 3. Relative response of General Radio P35 magnetic clamp, (a) with 4g (rms) cross-motion at 2kHz, (b) without cross-motion.

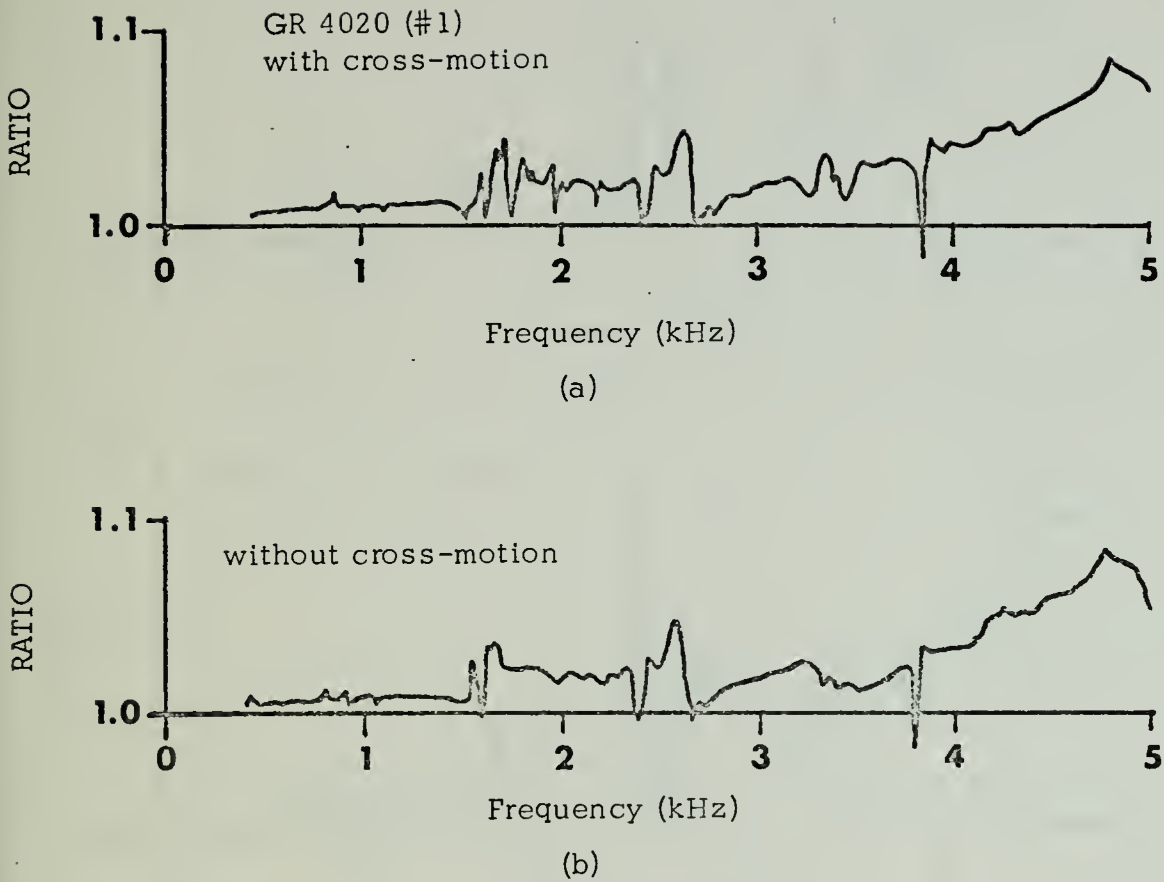
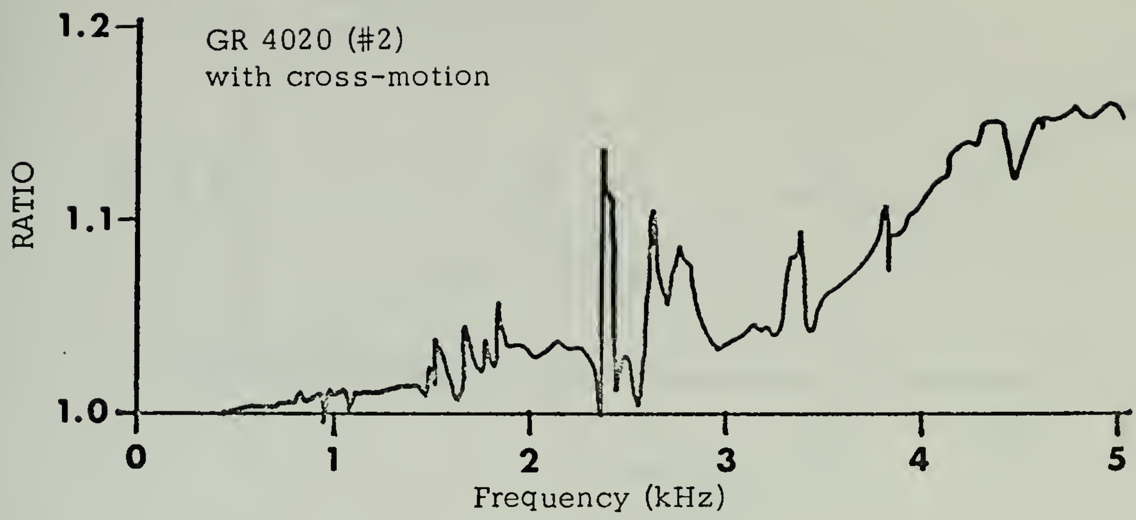


Figure 4. Relative response of General Ragio 4020 magnetic clamp (#1), (a) with 4g (rms) cross-motion at 2 kHz, (b) without cross-motion.



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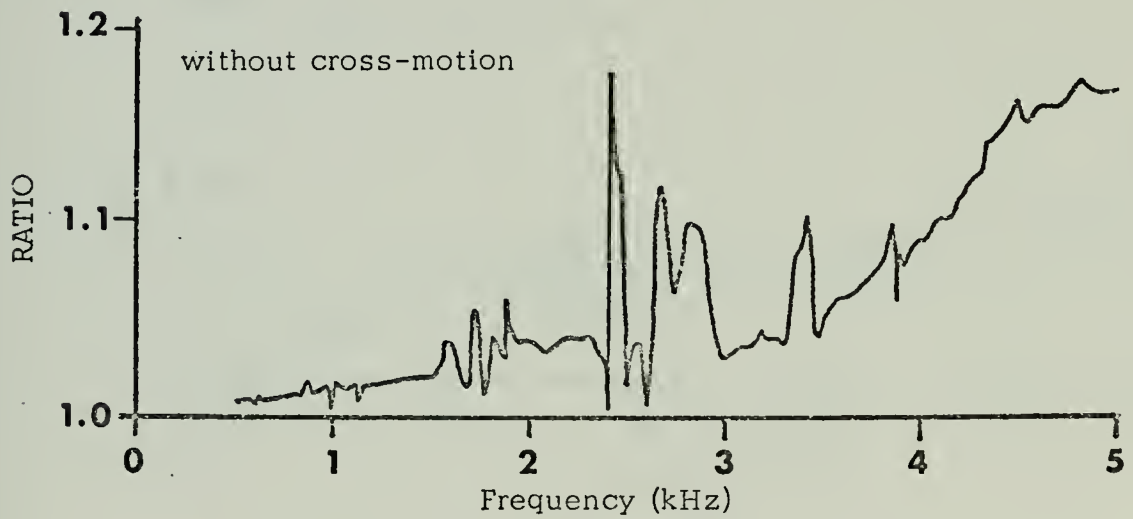
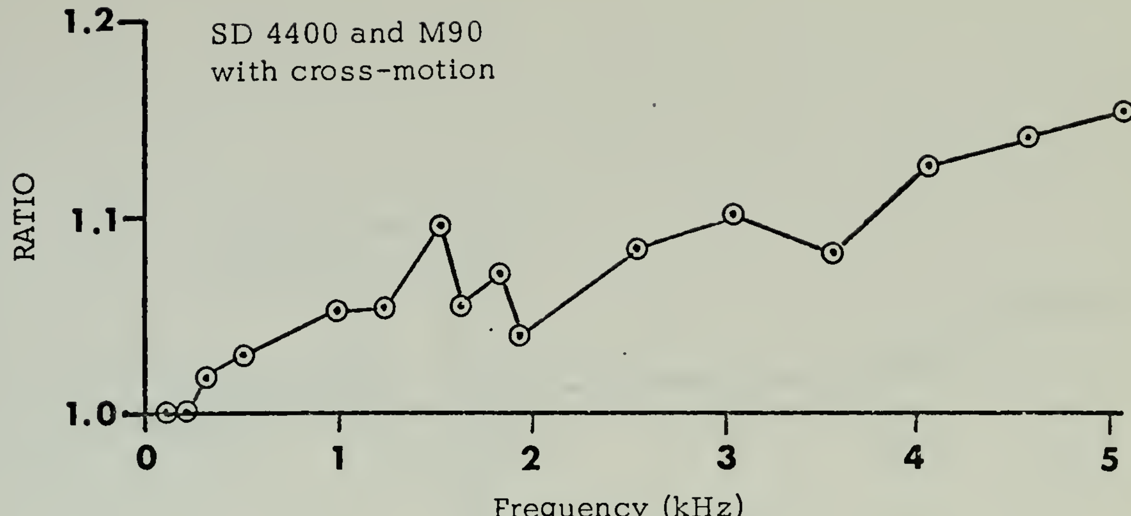


(b)

Figure 5. Relative response of General Radio 4020 magnetic clamp (#2) (a) with 4g (rms) cross-motion at 1 kHz, (b) without cross-motion.



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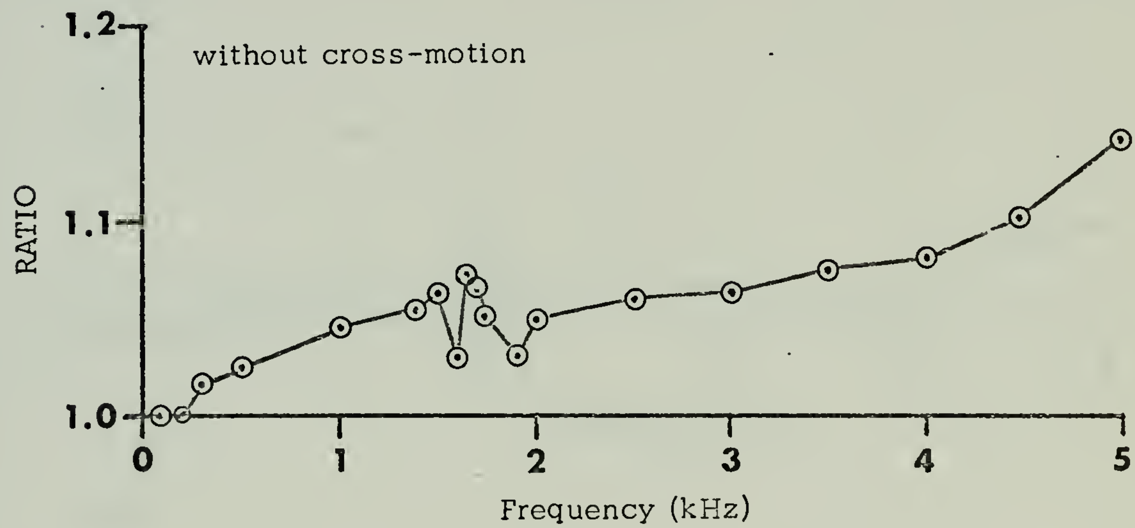


(b)

Figure 6. Relative response of Spectral Dynamics 4400 magnetic clamp and M90 accelerometer (a) with 4g (rms) cross-motion at 500 Hz, (b) without cross-motion.

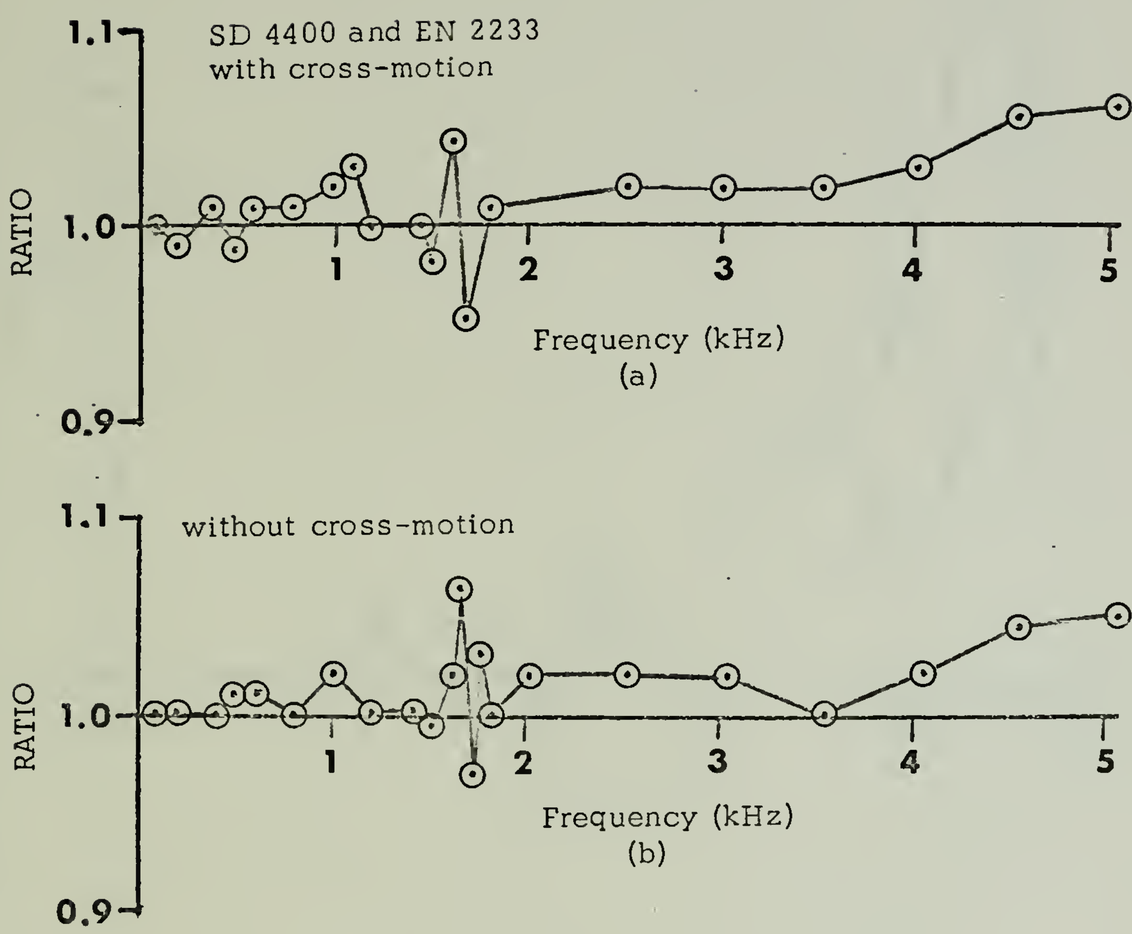


Figure 7. Relative response of Spectral Dynamics 4400 magnetic clamp and Endevco 2233 accelerometer, (a) with 4g (rms) cross-motion at 500 Hz, (b) without cross-motion.

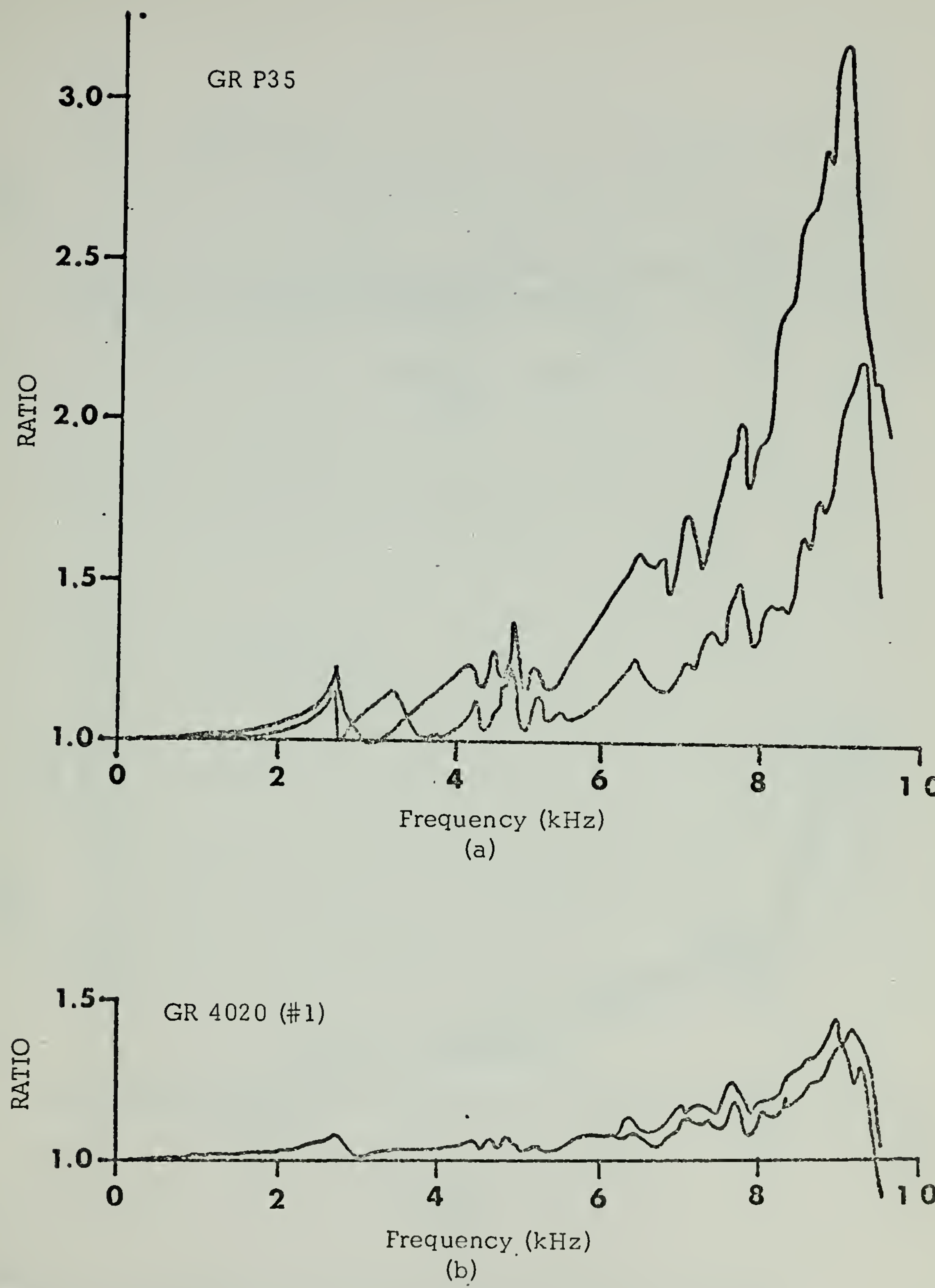
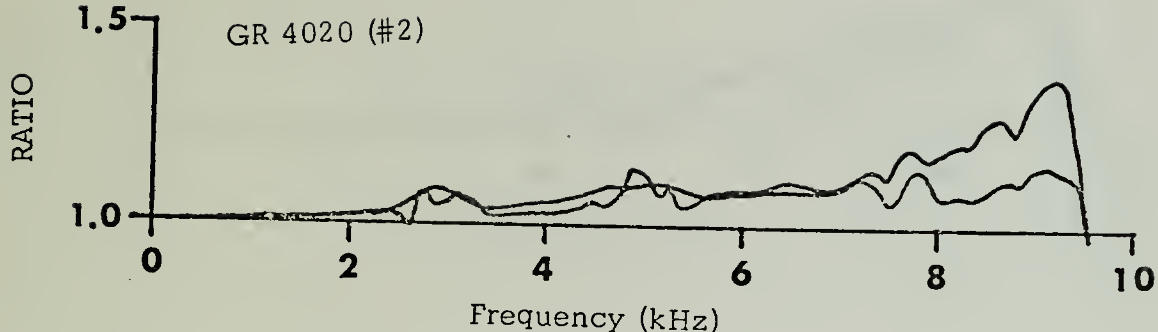
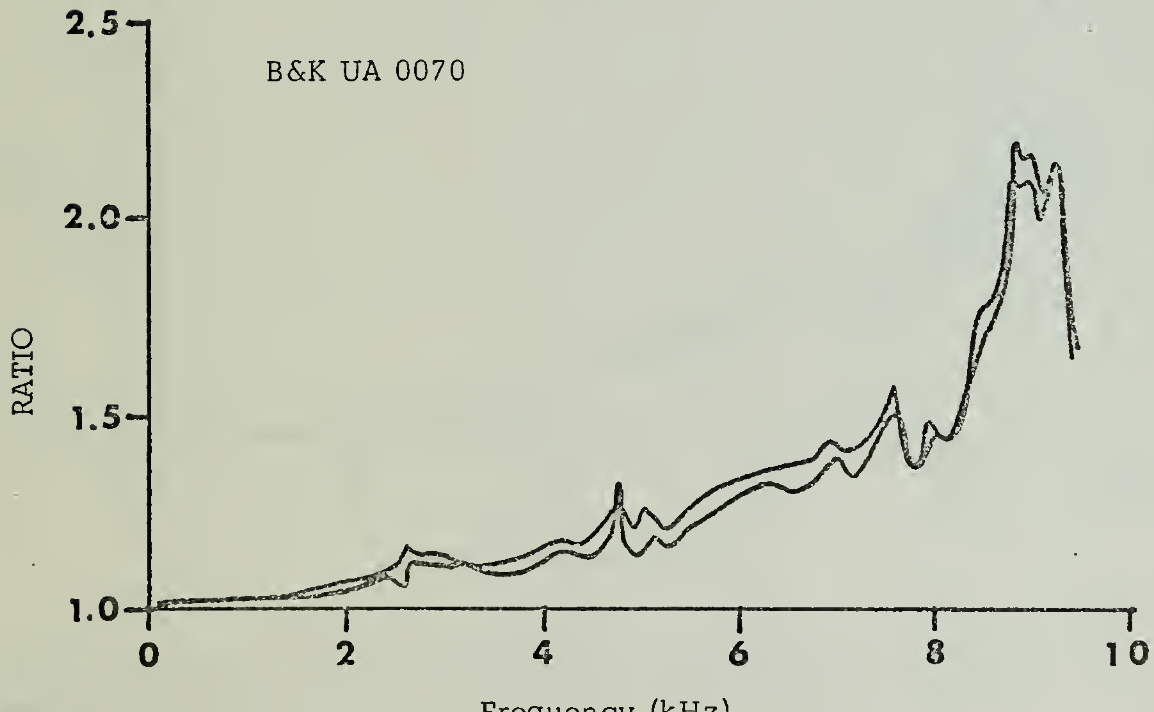


Figure 8. Best and worst relative response obtained with EN 2233 accelerometer mounted on (a) GR P35 magnetic clamp, (b) GR 4020 magnetic clamp (#1).



(a)



(b)

Figure 9. Best and worst relative response obtained with EN 2233 accelerometer mounted on (a) GR 4020 magnetic clamp (#2), (b) B&K UA 0070 magnetic clamp.

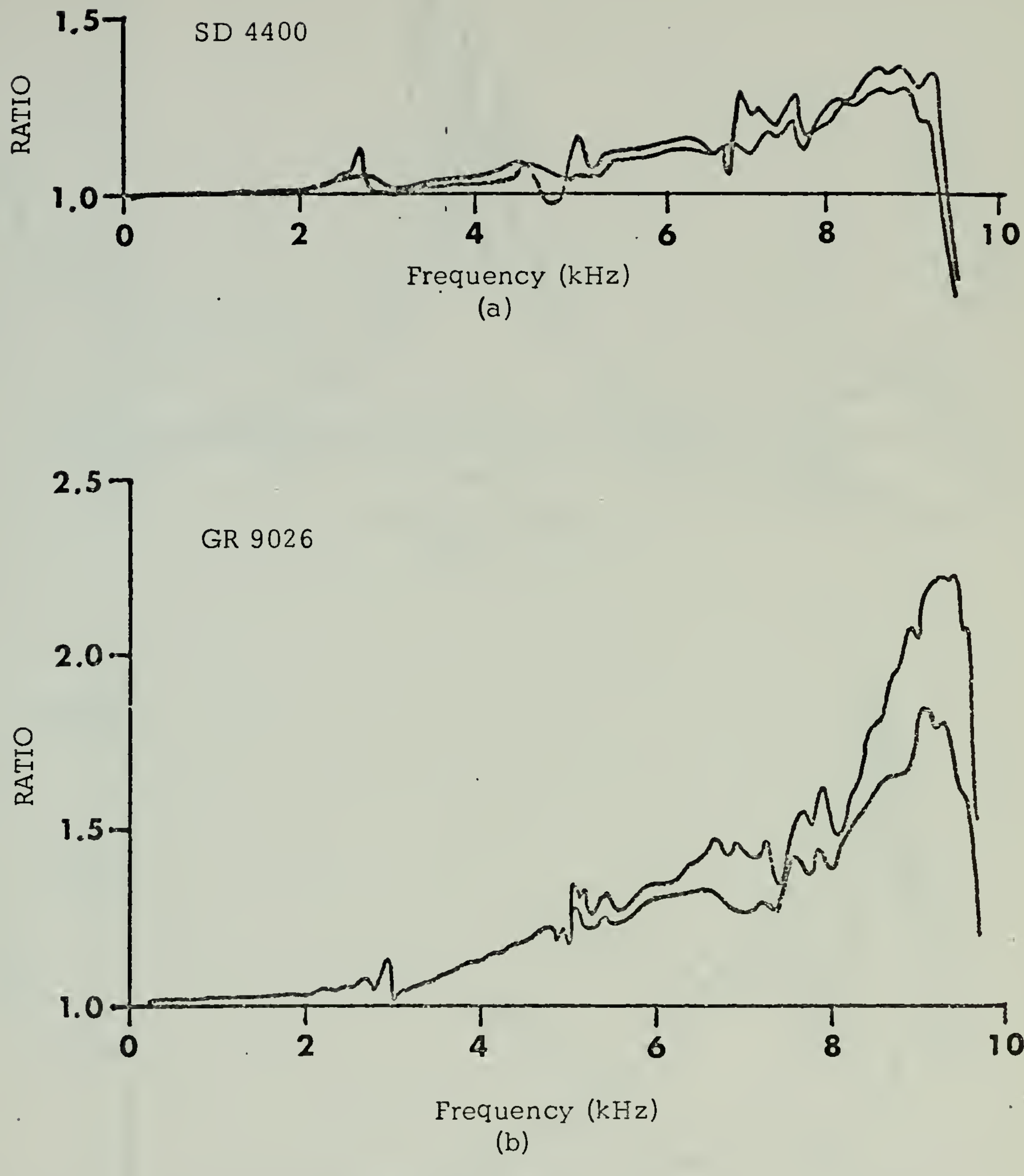


Figure 10. Best and worst relative response obtained with EN 2233 accelerometer mounted on (a) SD 4400 magnetic clamp, (b) GR 9026 magnetic clamp.

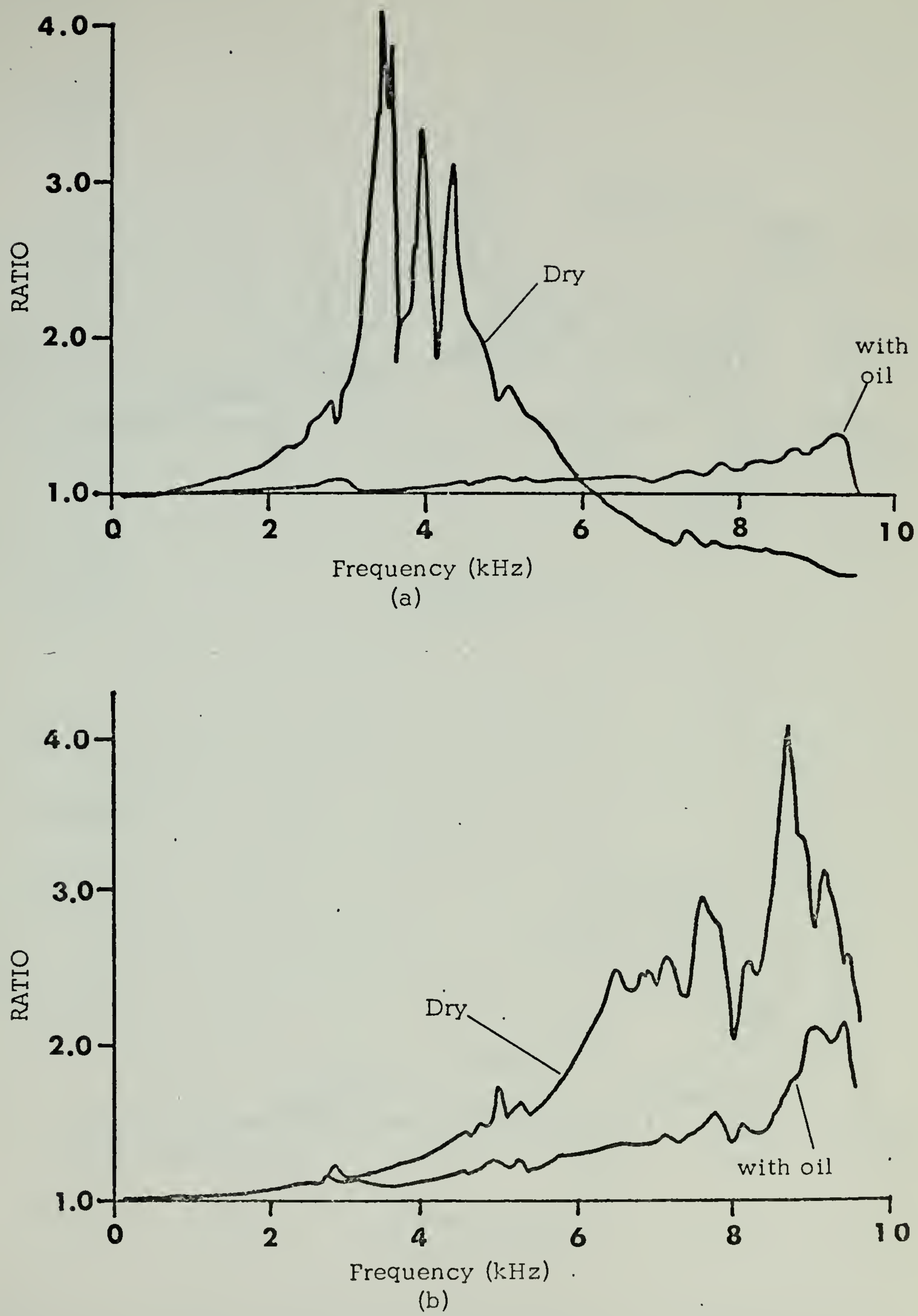


Figure 11. Comparison of relative response of magnetically mounted EN 2233 accelerometer with oil to that without oil between surface and magnet, (a) response for GR P35 magnet, (b) response for B&K UA 0070 magnet.

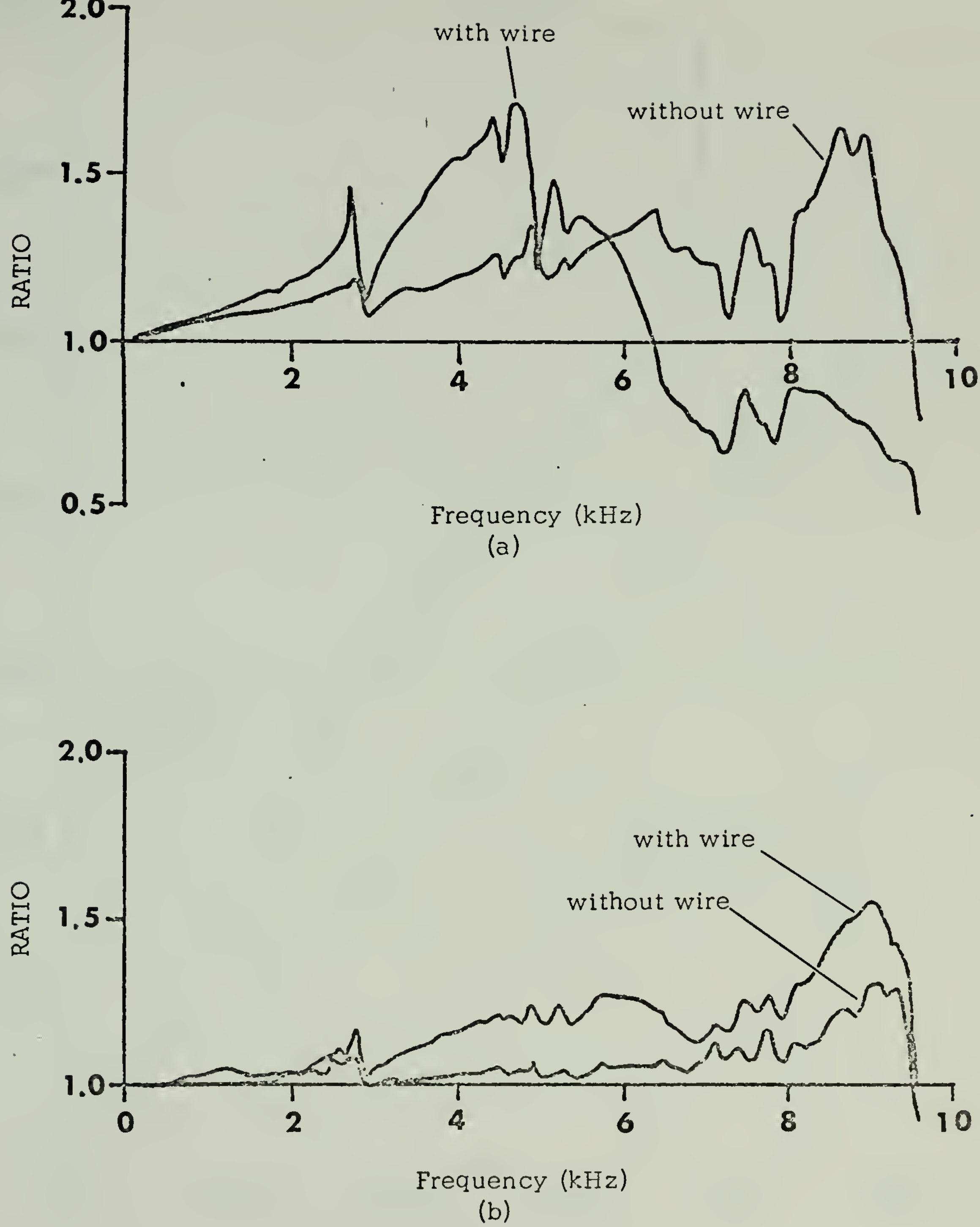


Figure 12. Effect of .001 in. iron wire placed under one leg. of magnetic clamp. Shown are the relative response curves for (a) SD 4400 magnet with M90 accelerometer, (b) GR 4020 magnet (#1) and EN 2233 accelerometer.

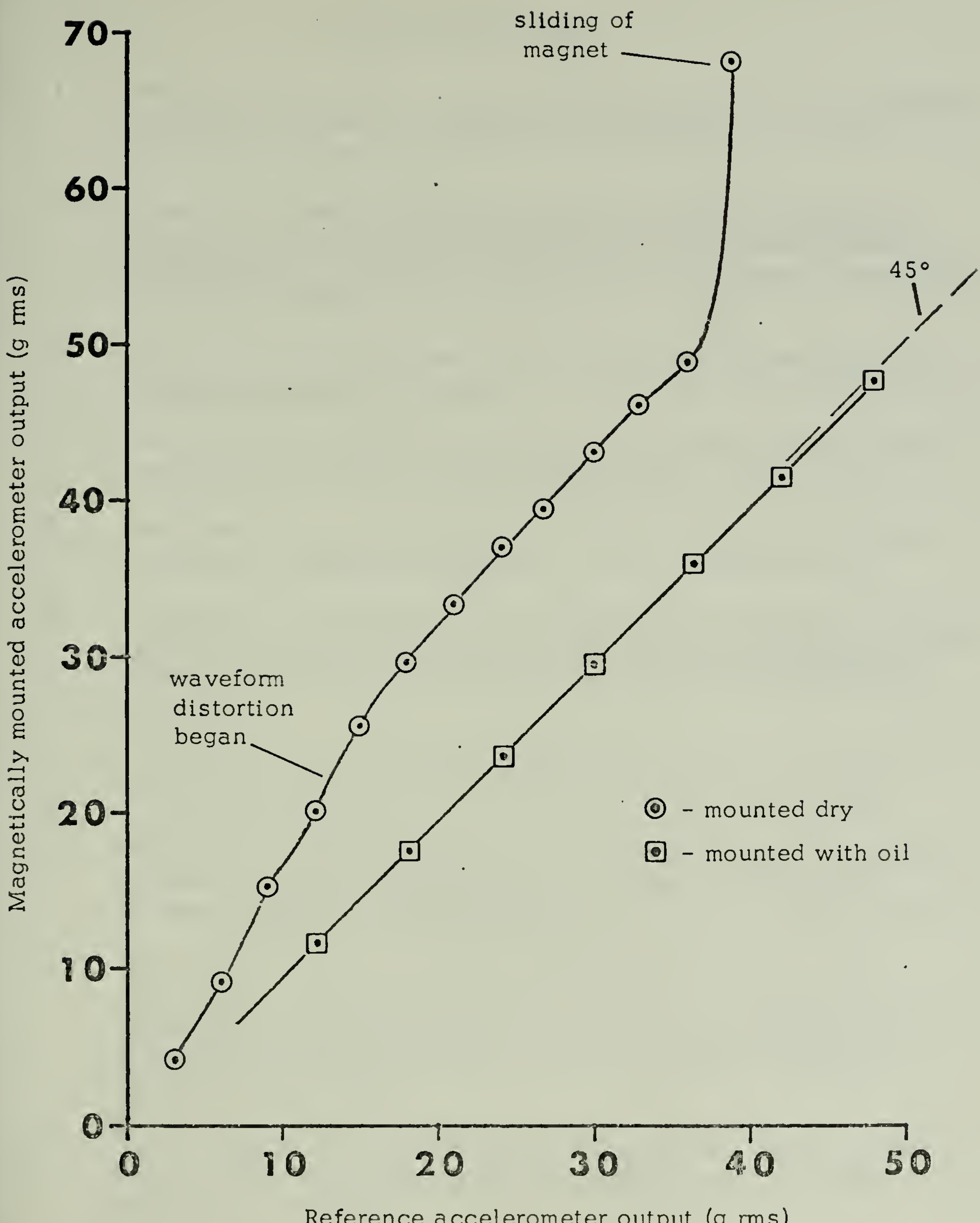


Figure 13. Effect of high acceleration level at 4 kHz on response of accelerometer mounted with General Radio 4020 magnetic clamp.

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